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Article

Towards Life Cycle Sustainability Assessment

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Abstract: Sustainability is nowadays accepted by all stakeholders as a guiding principle for both public policy making and corporate strategies. However, the biggest challenge for most organizations remains in the real and substantial implementation of the sustainability concept. The core of the implementation challenge is the question, how sustainability performance can be measured, especially for products and processes. This paper explores the current status of Life Cycle Sustainability Assessment (LCSA) for products and processes. For the environmental dimension well established tools like Life Cycle Assessment are available. For the economic and social dimension, there is still need for consistent and robust indicators and methods. In addition to measuring the individual sustainability dimensions, another challenge is a comprehensive, yet understandable presentation of the results. The “Life Cycle Sustainability Dashboard” and the “Life Cycle Sustainability Triangle” are presented as examples for communication tools for both experts and non expert stakeholders.

Keywords: life cycle sustainability assessment; life cycle assessment; life cycle costing; social LCA

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1. Introduction

The main drivers for the scientific developments towards Life Cycle Sustainability Assessment (LCSA) are the paradigm shift from environmental protection towards sustainability (see Section 1.1) and the current developments with regard to evaluation methods and tools for environmental and sustainability performance (see Section 1.2).

1.1. From Environmental Protection towards Sustainability

The global society has undergone a paradigm shift from environmental protection towards sustainability [1]. Sustainability does not only focus on the environmental impact, it rather consists of the three dimensions "environment", "economy" and "social well-being", for which society needs to find a balance or even an optimum [1,2].

The concept of sustainable development was first described in 1987 by the World Commission on Environment and Development under the leadership of the former Norwegian Prime Minister Brundtland [2]. It describes a development that is capable to cover today's needs for an intact environment, social justice and economic prosperity, without limiting the ability of future generations to meet their needs. The preservation of the natural environment is a prerequisite for a well-functioning economy and social justice. Thus it is necessary to bring the three pillars of sustainability—environment, economy, social well-being in harmony in all areas of life, both nationally and internationally.

These developments show the progress of a "traditional" to a "modern" environmental policy, whose characteristics are summarized in Table 1. The borderline between these two types is obviously not sharp and "modern" is not per se better than "traditional". However, the switch from reactive, national, single-issue and government driven environmental protection approaches based on end-of-the-pipe solutions towards an active, international, multi-criteria and stakeholder driven sustainability approach based on integrated solutions can be seen as central changes of the paradigm shift.

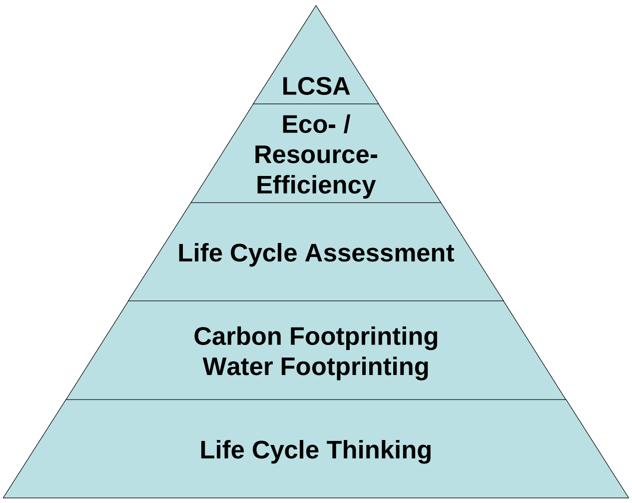
Table 1. Typification of the paradigm shift from "traditional" towards "modern" environmental protection approaches (based on Rubik [3])

Characteristics	**"TRADITIONAL" environmental protection**	**"MODERN" environmental protection**
political background	control of risks, dangers	sustainability ("triple bottom line")
primary policy principle	command & control	push & pull
main actor	governments	society ("shared responsibility")
policy setting	confrontation	cooperation
tasks	separation of tasks, individual solutions	integration of tasks, system solutions
principle for action	reactive	proactive
regional scope	local, national	international
focus	production ("single processes")	products ("process networks")
environment	single compartments and emissions	complete cross-media view over the complete life cycle
environmental technology	separate processes, end-of-pipe	integrated processes, innovations

1.2. Maslow's Pyramid of Environmental and Sustainability Assessment Tools

Over the last decades numerous assessment methods and tools for environmental and sustainability performance have been developed. They are grouped in Figure 1 according to an adapted pyramid of needs from Maslow [4]. While the original pyramid of Maslow has the basic physiological needs like food and breathing at the bottom, followed by safety needs, love and belonging, esteem until self-actualization at the very top, the adapted version starts with the basic approach of Life Cycle Thinking, followed by single-issue methods like Carbon or Water Footprinting, Life Cycle Assessment (LCA), Resource or Eco-efficiency Assessment up to Life Cycle Sustainability Assessment (LCSA) at the top of the pyramid (see Figure 1).

Figure 1. Adaptation of Maslow's pyramid of human needs for life cycle based environmental and sustainability assessment approaches.



Life Cycle Thinking represents the basic concept of considering the whole product system life cycle from the "cradle to the grave". It aims to prevent individual parts of the life-cycle from being addressed in a way that just results in the environmental burden being shifted to another part. Life Cycle Thinking has for example been addressed as one of the five key principles of the Integrated Product Policy of the European Union [5].

Life Cycle Thinking is a qualitative concept. With the next level in the pyramid the approaches start to be quantitative. More recently, evaluation approaches for single environmental issues like Carbon Footprinting [6] and Water Footprinting [7] have received considerable attention. They use the life cycle concept but address only one environmental impact, *i.e.*, climate change or water scarcity.

The next level is represented by Life Cycle Assessment (LCA). LCA is built around the principle of comprehensiveness and therefore aims to address all environmental interventions—not just one [8]. LCA is a well established environmental management tool for which international standards are available in their second generation [9,10].

With the next level, the purely environmental focus is left and economic aspects come into play. Both resource efficiency and eco-efficiency assessment approaches combine environmental indicators with economic indicators. On top of the pyramid, the last missing sustainability dimension, *i.e.*, the social one, is added to the other dimensions as part of a full life cycle based sustainability assessment.

The Maslow pyramid of environmental and sustainability assessment should be interpreted similar to the original pyramid on human needs. The hierarchy does not imply any ranking of which tool is better than another. It rather implies different levels of sophistication and therefore can be used to define development paths. If organizations or stakeholders have just started with integrating sustainability considerations into their processes and practices Life Cycle Thinking is a good starting point. If climate change is the most relevant issue in some parts of the globe and water scarcity in others, it is fair to start the more quantitative assessments with the respective single-aspect tools. Once this is done, these organizations can develop themselves into more complete environmental assessments (LCA). Once this level is reached, the other sustainability dimensions can be integrated.

The purpose of this paper is to give an overview of Life Cycle Sustainability Assessment (LCSA) and to describe the basic methodological features and examples of possible evaluation schemes, namely the "Life Cycle Sustainability Triangle" and the "Life Cycle Sustainability Dashboard". The following sections of this paper address Life Cycle Sustainability Assessment. The basic methodological features will be described in Section 2 while two examples of possible evaluation schemes are introduced in Section 3.

2. Life Cycle Sustainability Assessment Methodology

The first conceptual ideas leading to the LCSA approaches of today can be attributed to the German Oeko-Institut with their method called "Product Line Analysis" (German: Produktlinienanalyse) [11] and later O'Brian *et al.* [12]. Kloepffer put the LCSA framework into the conceptual formula (1) in 2007 [13] which was improved into its current form (1) including editorial hints of Renner and Finkbeiner [14].

$$\begin{gathered} \text{LCSA = LCA + LCC + SLCA} \\ \text{LCSA = Life Cycle Sustainability Assessment} \\ \text{LCA = Environmental Life Cycle Assessment} \\ \text{LCC = LCA-type Life Cycle Costing} \\ \text{SLCA = Social Life Cycle Assessment} \end{gathered} \tag{1}$$

The following sections summarize the state-of-the art with regard to the environmental dimension (see Section 2.1.), the economic dimension (see Section 2.2.) and the social dimension (see Section 2.3.) of LCSA.

2.1. Environmental Dimension

LCA represents the state of the art in science and application relating to the environmental dimension of sustainability. The international standards ISO 14040 and 14044 are now the main reference system in performing LCAs [9,10]. LCA is a holistic, system analytic tool and is now an established and integral part of the environment management tools. LCA is distinguished from other environmental assessment tools by two main features [15]:

- Life cycle perspective:
  all phases ("from the cradle to the grave") of the life cycle of a product (good or service)—from the extraction and processing of the resources, over production and further processing, distribution and transport, use and consumption to recycling and disposal—have to be assessed with regard to all relevant material and energy flows.
- Cross-media environmental approach:
  all relevant environmental impacts are taken into account, *i.e.*, both on the input side (use of resources) and on the output side (emissions to air, water and soil, including waste).

According to ISO 14040 LCA is defined as "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". Further details on the current state-of-the-art methodology can be found for example on the publications pages of the European Platform of Life Cycle Assessment or the UNEP/SETAC Life Cycle Initiative [16,17].

Apart from standardization bodies, the mentioned UNEP/SETAC Life Cycle Initiative plays a relevant role in the application and dissemination of LCA. A survey undertaken to assess the capability development of LCA revealed that LCA capacity of certain levels could be already identified for more than 80 countries globally [16].

2.2. Economic Dimension

For the economic dimension of sustainability, there are a variety of approaches for the calculation of cost and performance. The economic evaluation is usually done by considering manufacturing costs (from a business perspective) and life cycle costs (from the customer's perspective) [18,19].

The life cycle costs are the total costs of a system or product, produced over a defined life time [20,21]. The synonyms 'total costs' or 'total life cycle costs' indicate the coverage of all costs; without assigning them to a cost unit. If the assessment or design (planning, accumulation and control) is limited to actual cost, one can refer to it as life cycle costing in a narrow sense [22]. Including further performance parameters can be addressed by life cycle costing in a broader sense. A key challenge for life cycle costing is the different possible perspectives when considering the life cycle costs [23]. The variety of possible viewpoints for an investigation—from producer perspectives via customer perspectives to societal perspectives—leads to a correspondingly large number of different methods. As a consequence, the term life cycle costing is used for total-cost-of-ownership assessments as well as external or social cost assessments.

A recent book developed by a working group of SETAC defined the term "Environmental Life Cycle Costing" in the senses of "…an assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle (…) with complimentary inclusion of externalities that are anticipated to be internalized in the decision-relevant future." (p. 173). Approaches that fall under this definition are particularly meaningful with regard to LCSA, because they are consistent with the environmental dimension and avoid double-counting [24].

One example of such a method is the life cycle costing approach developed by Bubeck [25], which considered in analogy to LCA an individual product as a reference object and which is already applicable at the stage of product development. This requires a structuring of the costs according to life cycle stages, the focus on money flows (in analogy to material and energy flows) and taking the perspective of the user of the product.

2.3. Social Dimension

The social dimension of sustainability captures the impact of an organization, product or process on society. The social benefits can be estimated by analyzing the effects of the organization on stakeholders at local, national and global levels [26]. The majority of social indicators measure the degree to which societal values and goals in the particular areas of life or politics can be achieved. However, many social issues on which a performance measurement takes place are not easy to quantify. Therefore a number of social indicators contain qualitative standards of systems and activities of the organization, including operating principles, procedures and management practices. These indicators address needs specific to social issues such as forced labour, working hours or existence of trade unions.

The topic of SLCA is currently still in its infancy but an increasing number of scholars and institutions is engaging in SLCA research. A review and current challenges of SLCA have been published by Jørgensen *et al.* [27-29]. Recently, UNEP published Guidelines for Social Life Cycle Assessment of Products [30] which address the overall concepts and methods of SLCA.

However, the selection of social criteria and their quantification is still one of the major challenges when implementing the concept of sustainability. There are still research needs and consensus needs of the involved stakeholders. There is currently no uniform usage of a standardized set of indicators, but operationally applicable indicators are available. An extensive research on sustainability indicators with focus on the "social" dimension gave a total of over 150 proposals for different social objectives and indicators [31].

The analysis showed that a variety of social objectives and indicators address many different topics, such as politics, society, women rights or health, that can be partitioned in individual needs (e.g., protection and improvement of human health, creating a balanced settlement structure, education and others) and societal goals (e.g., social responsibility in companies, examination of the size and distribution of population). The diversity and the varying quality of the over 150 identified social sustainability indicators show that one can not directly derive a coherent and practical approach of social indicators for products or processes. In addition, the analysis revealed that only very few indicators can be directly assigned to products or processes. For many indicators, such as UN Global Compact, the existence of a work council or the availability of an annual report, there is a reference to organizations (usually businesses). Most of the indicators, however, apply to regions/countries, such as the Human Development Index (HDI), the density of the road network, health expenses in % of Gross Domestic Product (GDP) or the number of welfare recipients per 1000 population. Some social indicators also include certain political aspects, such as the representation for the disabled, the Human Freedom Index (HFI) as well as municipal debt (debt of communities and organizations per citizen).

As a consequence, a problem for an operationally feasible approach is that no straightforward applicable social indicators can be directly attributed to products or processes. Thus, one must use indicators of another reference level (organizations, regions) and the product relation must then be made via appropriate methodological assumptions.

The next big challenge is data availability. An application oriented set of indicators must be based on those social objectives and indicators, which can be operationally evaluated at the current level of knowledge and data status. This means that simple data availability and applicability of the social objectives and indicators are a top priority. Simple data availability means, that the required data is available in publicly accessible data sources. This eliminates the indicators that are only accessible through extensive individual data collection of the companies involved in the product system, as this would involve enormous effort when taking the life cycle approach into account. The premise of 'public data availability' leads currently to an approach with only three indicators:

- Human Development Index (HDI) [32]: data accessible in the annual Human Development Reports.
- Gini-coefficient as a measure of inequality of wealth [33]: data accessible in the annual Human Development Reports (http://hdr.undp.org) and
- Commitment to comply with the criteria of the UN Global Compact [34]: data accessible in the weekly updated index.

It should be noted that none of the three indicators has a direct relation to the products, which leads to specific problems of integration into the product model. Furthermore, the HDI and the UN Global Compact criterions are aggregated indicators, where the HDI includes the education levels, health levels and living standards, and the UN Global Compact criterion contains issues of human rights, working standards, environment and anti-corruption. A Gini-coefficient can be used for both income- or wealth distributions. This is certainly not an ideal solution, but as of today at least operationally possible.

3. Life Cycle Sustainability Assessment Evaluation Schemes

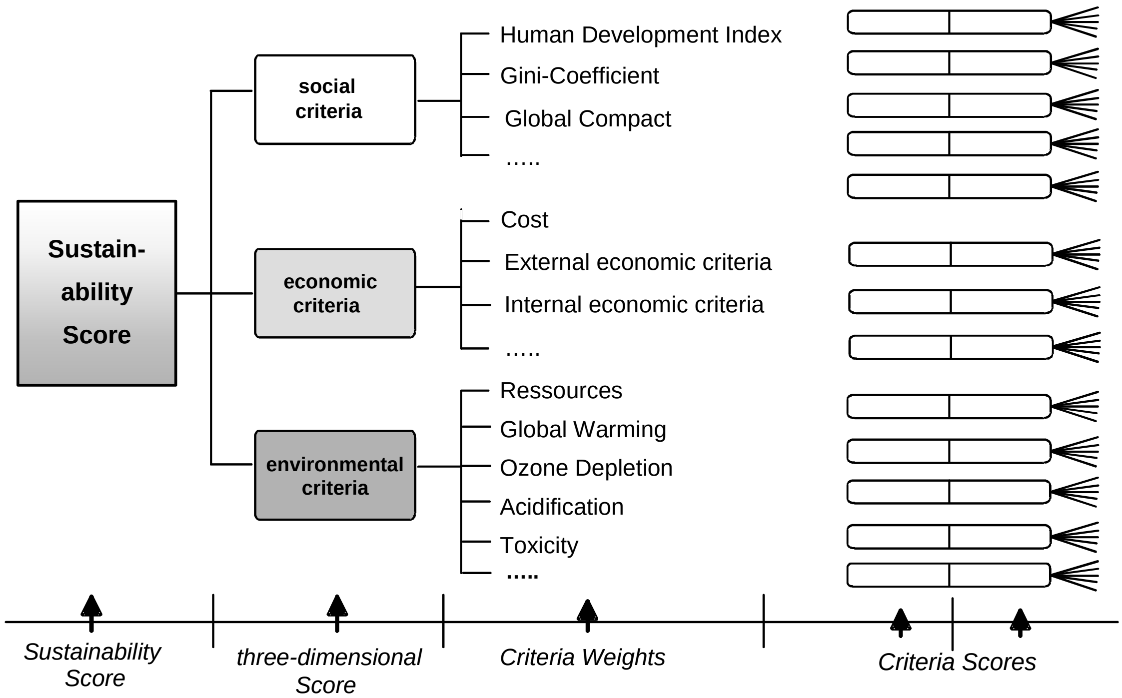
Apart from the indicators discussed above LCSA requires an appropriate multi-criteria evaluation scheme. Such an evaluation scheme has to address the scales and target levels of the indicators as well as the weighting between them. For LCSA the weighting problem exists on at least two levels:

- weighting of individual indicators within each of the three sustainability dimensions, *i.e.*, weighting between e.g., different environmental indicators like global warming potential and acidification potential (the same applies to social and economic indicators), and
- weighting among the three dimensions of sustainability (environmental, economic, social).

The decision making situations in the field of sustainability management are very diverse. Regarding the number of goals several objectives and criteria have to be considered. There are also very often trade-offs between these goals, which need to be addressed with the appropriate procedures [35] and which have to be addressed by the multi-criteria-analysis [36]. The trade-offs between the three dimensions of sustainability need to be addressed with utmost care in order to keep a sustainable balance. However, ignoring or neglecting that weighting happens in real world decision making anyway—at least implicitly—is not a feasible option for developing evaluation schemes. While it is not our intention to recommend to do weight the three sustainability dimensions into a single-score, the following schemes still allow to do that in a transparent rather than an implicit way, if the decision-makers decide to apply quantitative weighting. The chosen utility analysis approaches have the advantage that in addition to quantitative criteria also qualitative assessments can be considered and presented in the same assessment scheme.

For the purpose of LCSA the life cycle engineering framework developed in the group of Eyerer which addresses the three dimensions technology, economics and ecology [18,19] can be adapted to a sustainability utility analysis. The basic idea of the adaptation of the life cycle engineering to the sustainability utility analysis is to replace the dimension "technology" by the dimension "social". For a pure utility approach, it would be possible to add the social dimension as a fourth component. But some graphical evaluation options like the Life Cycle Sustainability Assessment Triangle (see Section 3.2) are constraint by a maximum of three dimensions. A general evaluation scheme with exemplary indicators for a LCSA utility analysis is presented in Figure 2.

Figure 2. LCSA evaluation scheme addressing all three sustainability dimensions.



To support decision-making LCSA results are faced with the challenge to be difficult to understand and to interpret for a non-expert audience. But non-experts are usually represented in the target audience of the decision-makers. Therefore, an understandable, yet comprehensive presentation of LCSA results is a key challenge for the application of LCSA [37]. Two approaches that try to address this challenge are introduced in the following sections; the Life Cycle Sustainability Triangle (see Section 3.1.) and the Life Cycle Sustainability Dashboard (see Section 3.2.).

3.1. Life Cycle Sustainability Triangle (LCST)

The Life Cycle Sustainability Triangle (LCST) is an adaptation of the representation used for chemical mixtures on the weighting problem which was adapted to weight different environmental impacts by Hofstetter *et al.* [38]. The graphical representation can be applied to the weighting of any three parameters. In the following example, the utility values social, economic and environmental aspects are to be weighted. These utility values are the input variables for the weighting procedure:

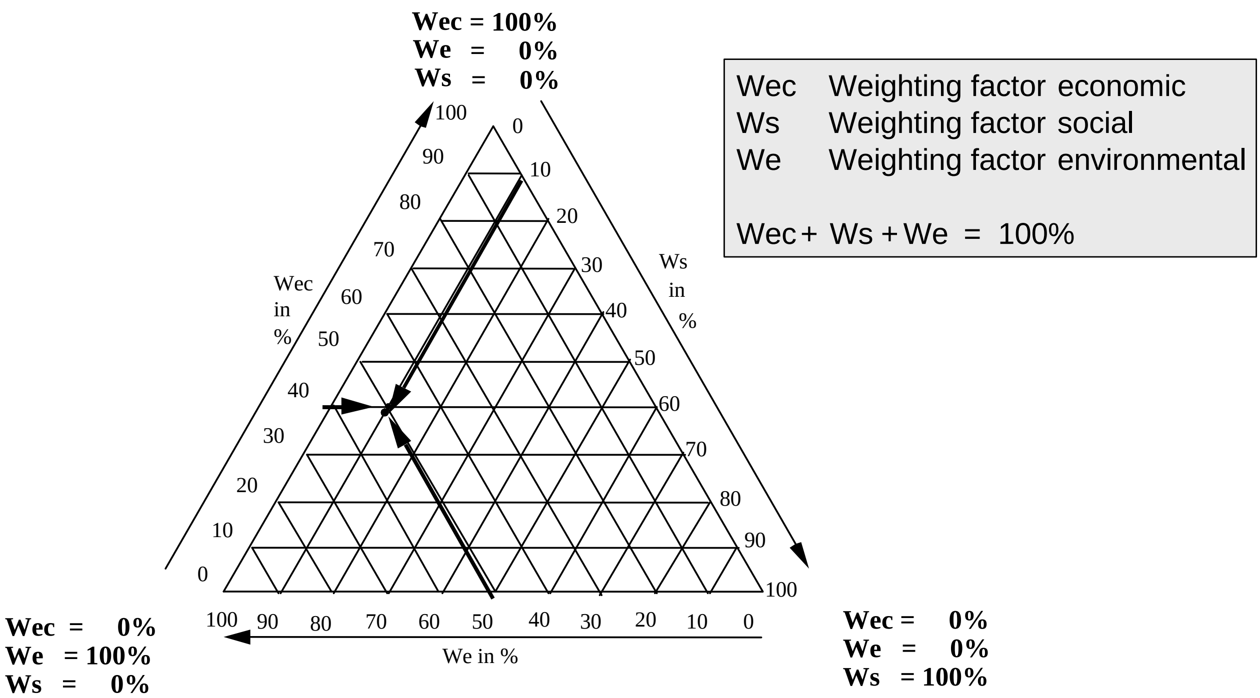
- environmental value: E_i
- social value: S_i
- economic value: Ec_i

The sustainability utility value or total utility value of an alternative is calculated by normalizing these three values, multiplying them by a weighting factor and then adding them together. The weighting factors are named We (for E_i), Ws (for S_i) und We (for Ec_i), the triple (We, Ws, Wec) is named weighting set. The weighting factors have the following relationship:

$$We + Ws + Wec = 100\% \qquad \text{and} \qquad We, Ws, Wec > 0$$

In Figure 3 the illustration of the various weighting sets is introduced. In the three corners of the LCST diagram are the weighting factors, We, Ws und Wec. Each point in the triangle area corresponds to a specific weighting set (We, Ws, Wec). In Figure 3 all possible weighting combinations between the three sustainability dimensions can be displayed as a reference point. For example, a point with the weighting set (We = 0.4; Ws = 0.1; Wec = 0.5), which corresponds to a weighting of 40% of the environmental utility value, a social utility value of 10% and an economic utility value of 50%, can be drawn into the triangle by marking the values on the appropriate axes and connecting these three points as shown in Figure 3.

Figure 3. LCST graphical scheme with exemplary weighting set.



An example illustrating a comparison of two alternatives A and B is shown in Figure 4. At each weighting set reference point the dominant alternative, *i.e.*, the alternative with highest sustainability utility score for the corresponding weighting set, is shown. This leads to a graphical representation of two dominance areas separated by a straight equilibrium line. The interpretation can be done by following the dominance patterns along the axes, starting from the corners:

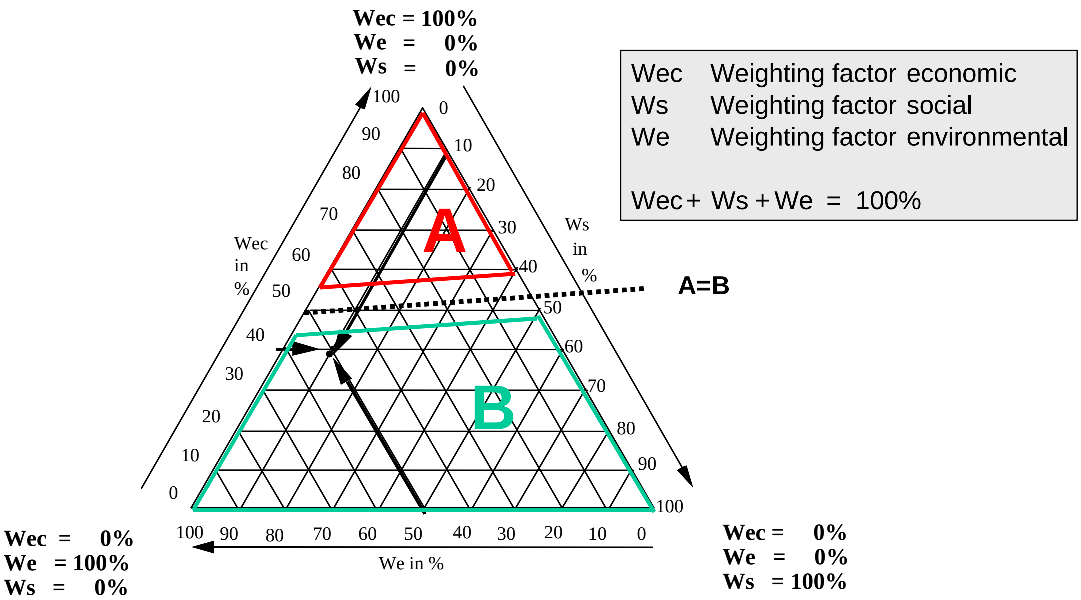
- Environmental Performance

  At the upper corner (point 1) environment is weighted at 100%. If the decision is solely based on environmental criteria, alternative A is chosen. If one now follows the environmental axis up to point 2, the dominance changes, *i.e.*, option A is now only preferred if environment is weighted at least 53%. At a lower weighting of environmental performance alternative B always dominates.
- Social Performance

  At the right corner (point 3) the social dimension is weighted at 100%. If the decision is solely based on social criteria, alternative B is chosen. If one now follows the social axis up to point 4 the dominance field changes, *i.e.*, in a purely socio-environmental weighting a social weighting of below 43% would lead to a preference of option A. If one includes the economic dimension, option B can also dominate with a social weighting of only 10% if the economic performance is weighted by more than 50% (point 5).
- Economic Performance

  On the left corner (point 6) economic performance is weighted at 100%. If the decision is solely based on economy, alternative B is chosen. A weighting of 47% corresponds to point 7 on the economy axis. If economic performance is weighted at least with this value alternative B always dominates.

Figure 4. LCST graphical scheme for a comparison of two alternatives A and B.



Initially, the LCST graphs may take some time to get used to them. However, by conducting several examples, the familiarity with the LCST increases quickly and allows to show the preference for an alternative for all possible weighting sets of the three sustainability dimension at one glance.

3.2. Life Cycle Sustainability Dashboard (LCSD)

Another evaluation scheme proposed by Traverso and Finkbeiner [37] is the Life Cycle Sustainability Dashboard (LCSD). It is a specific application of the Dashboard of Sustainability to

LCSA. The Dashboard of Sustainability methodology [39,40] and the related software were established by a research group of the Joint Research Centre of Ispra, Italy. It was originally developed to assess several communities by integrating economic, social and environmental factors. The functionality of the Dashboard is now scientifically supported by the International Institute for Sustainable Development (IISD) to further develop the aggregation and communication functionality.

In the Dashboard of Sustainability software a certain number of indicators and their values can be inserted. The indicators are grouped into a limited number of topics. It is therefore possible to set up an own dashboard choosing the appropriate topics and associated indicators. For the application to LCSA simply the indicator sets used for LCA, LCC and SLCA can be used and implemented. After that all indicator values for each considered product can be entered into the software which ranks all values for each indicator and gives 1000 points to the product with the best performance (dark green in the colour scale) and 0 points to the worst performance (dark red in the colour scale). All other values of the same indicator are linearly interpolated. Weighting factors to the indicators can be handled by the software, too. The evaluation results for each topic are given by a weighted average of all included indicators values; the overall evaluation is the arithmetical average of the topic evaluations. As for the indicator values the resulting evaluations are obtained by scores (between 0 and 1000) and according colours.

Figure 5. LCSD graphical scheme; individual results for LCA, LCC and SLCA in the upper part and lower right; overall LCSA result in the lower left; example shown is a comparison of different hard floor coverings.

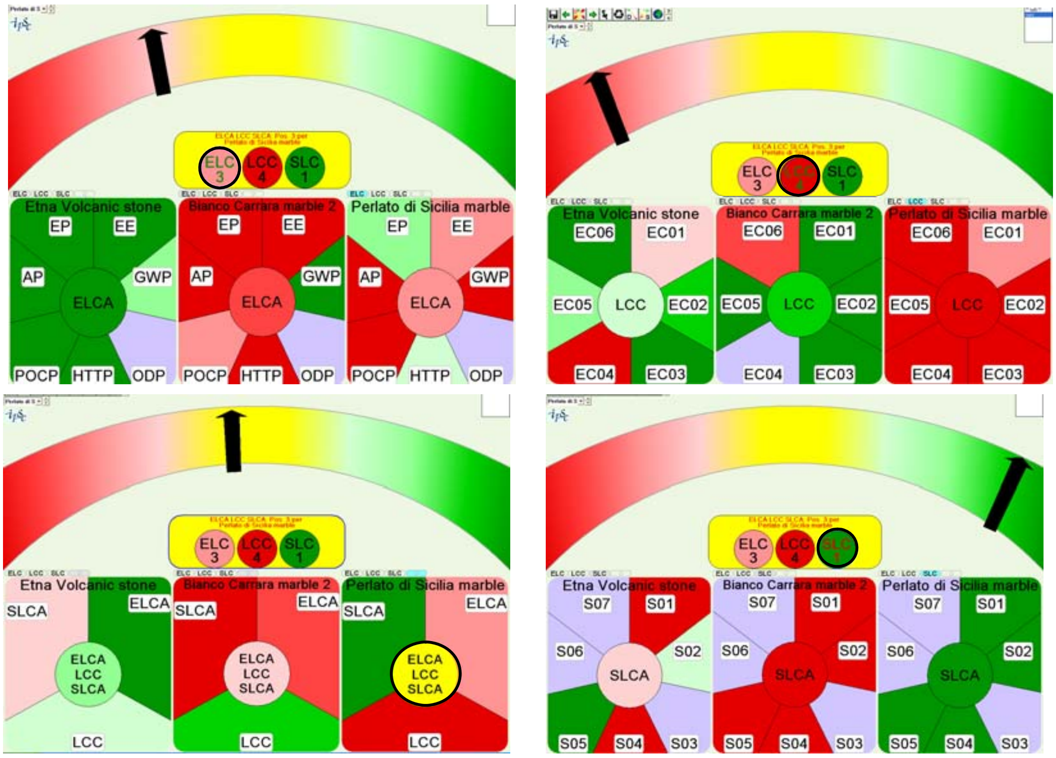


Figure 5 shows an example how the graphical result presentation of an LCSD can look like. It is characterised by the ability to present the results of the evaluation and the comparison of alternatives by means of a graphical representation (a cartogram) with an intuitive chromatic scale. The performance is displayed through a seven-colour code ranging from dark red that represents the "critical" conditions over yellow "average" conditions to dark green representing the "best"conditions. The violet colour indicates when data are not available. An additional feature is the dashboard arrow at the top of each graph which can be used to display the overall result or any chosen single indicator.

In the example shown in Figure 5 Etna Volcanic Stone performs best environmentally (dominant green area in upper left corner) while the Life Cycle Costing results show a slight preference for Carrara marble. The dominant red area of Perlato di Sicilia marble indicates the worst performance in LCC, but with regard to SLCA this alternative performs best. The arrow in the top of each graph shows the performance of Perlato di Sicilia marble.

4. Conclusions

While sustainability is nowadays accepted by all stakeholders as a guiding principle, the challenge to unambiguously determine and measure sustainability performance does remain, especially for products and processes. The maturity of methods and tools is different for the three sustainability dimensions. While the environmental dimension can be covered quite well today, the economic and social indicators and evaluation methods still need fundamental scientific progress. Life Cycle Thinking, Carbon and Water Footprinting, Life Cycle Assessment, Resource- and Eco-efficiency Assessment can be useful tools for supporting sustainable production and consumption, if their results are interpreted with proper consideration of their respective limitations. However, the concept of LCSA is ultimately the way to go. The life cycle perspective is inevitable for all sustainability dimensions in order to achieve reliable and robust results.

Apart from challenges with regard to indicators and weighting issues, LCSA has to deal with the trade-off between validity and applicability. The inherent complexity of an approach that is supposed to allow a valid measurement of the sustainability performance is a challenge for decision-makers. Therefore, effective and efficient ways to present LCSA results are needed. This is a prerequisite for the communication of LCSA results to the non-expert audience of real world decision-makers in public and private organizations. LCSA is intended to have a tangible effect on the sustainable development of our society. To achieve that, it has to become both valid and applicable.

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